AN EXAMPLE OF THE USE OF INTERDIGITAL PVDF TRANSDUCERS TO GENERATE AND RECEIVE A HIGH ORDER LAMB WAVE MODE IN A PIPE

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INTRODUCTION

From a non-destructive evaluation point of view, Lamb waves are a highly attractive means of inspecting a large area of a structure from a single point. Interdigital PVDF transducers have been used previously in signal processing applications [1] to generate acoustic waves in piezoelectric substrates. This paper in conjunction with that of Monkhouse et al [2] aims to provide an overview of the work accomplished so far at Imperial College in the use of interdigital PVDF transducers to transmit and receive Lamb waves in certain structures for non-destructive evaluation purposes. Interdigital PVDF transducers may be permanently bonded to either flat of curved surfaces and this attribute together with their low cost means that they are potentially suitable for "smart structure" applications.

After a brief summary of Lamb wave theory and transducer construction, an example of the application of interdigital PVDF transducers to a specific structure is presented, which illustrates many of the key points in their design, use and modelling. Firstly the factors involved in the selection of a suitable Lamb wave mode and the subsequent transducer construction are described. This is followed by descriptions of their experimental use and a finite element (FE) model of the application, together with the associated results from both.

LAMB WAVE THEORY

A class of acoustic waves that propagate in flat and curved plates of finite thickness are Lamb waves. The theory of Lamb waves is well known [3] but the key points may be summarised as follows. At any one frequency, more than one Lamb wave mode can exist and they will generally have different group and phase velocities. These two quantities may be obtained analytically as the modal solutions to the wave equation which satisfy the appropriate boundary conditions, and they are generally plotted against frequency to give the familiar dispersion curves. For practical testing work it is generally accepted that only a single mode must be excited in order for results to be interpretable. If multiple modes are excited then their speeds must be sufficiently different to enable them to be separated in time. As multiple modes may exist at any frequency the generation of a single mode requires excitation at both a particular frequency and a particular wavelength. Interdigital transducers provide an alternative method of achieving this excitation instead of using angle transducers [4] or EMATs [5].

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 16
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1997

TRANSDUCER CONSTRUCTION

The transducers used in this work were interdigital PVDF ones of the type which are described in more detail by Monkhouse et al [2]. In essence they consist of a layer of piezoelectric polymer (PVDF) bonded to the structure under test. A flexible PCB is bonded on top of the PVDF, copper side down, the PVDF being excited by a voltage difference between the PCB and the structure. The PCB is printed with two interleaved sets of comb shaped electrodes. The finger spacing of the combs defines the wavelength of the transducer and the individual finger widths are used to provide a spatial Hanning window effect over the region on which the transducer is bonded. The transmit and receive transducers are identical and electrically interchangeable.

EXAMPLE APPLICATION

The rest of this paper will be concerned with the design, modelling and testing of a pair of transducers for use in a specific application. As well as being an example of interdigital transducer usage, this case study also illustrates several points of interest, such as the effect of using the transducers on a thick curved structure, the use of higher modes and finite element modelling of the system.

Description

The structure in question was a 150mm diameter ductile iron pipe with a wall thickness of 6.5mm. The long term aim was to investigate the feasibility of using interdigital PVDF transducers for corrosion monitoring in pipes of this type. The transducers discussed here were one of three pairs made up to evaluate how successfully different Lamb wave modes could be transmitted and received circumferentially around the pipe.

Effect Of Curvature

The ability of interdigital PVDF transducers to conform to curved surfaces is one of their key attractions. However, it is important to understand to what degree the curvature of a structure will affect the propagation of Lamb waves within it. Fig. 1 shows the phase velocity dispersion curves for ductile iron plate, plotted using *Disperse*[6]. It can be seen that in the case of the pipe described above where the radius to wall thickness ratio was around 11.5, there would be negligible deviation from the dispersion curves for a plate, and hence for design and modelling purposes, the pipe was represented as a flat plate of the same thickness. Indeed it is not until below a radius to wall thickness ratio of around 8 that the deviation becomes significant. It is hard to envisage any practical case where interdigital transducers would be used to propagate circumferential waves around pipes of these dimensions. However, if they were to be used on flat plates containing folds, this type of result may be used to predict the amounts of transmission or reflection at such folds. Transmission and reflection coefficients could be calculated from the changes in phase velocity due to changes in curvature.

Selection Of Operating Point

Figs. 2(a) and (b) show respectively the phase and group velocity dispersion curves for a 6.5mm ductile iron plate, which were plotted using *Disperse* [6]. The first constraint on the selection of an operating point was that even with 50μm thick copper plated electrodes, interdigital PVDF transducers still only have a satisfactory response above about 0.75MHz [2]. Due to the thickness of the material, the non-dispersive points on the lower modes A_0, S_0 and A_1, which would be the preferred operating points on a thinner plate, were at frequencies too low to be used. Instead it was necessary to find an operating point on a higher mode.

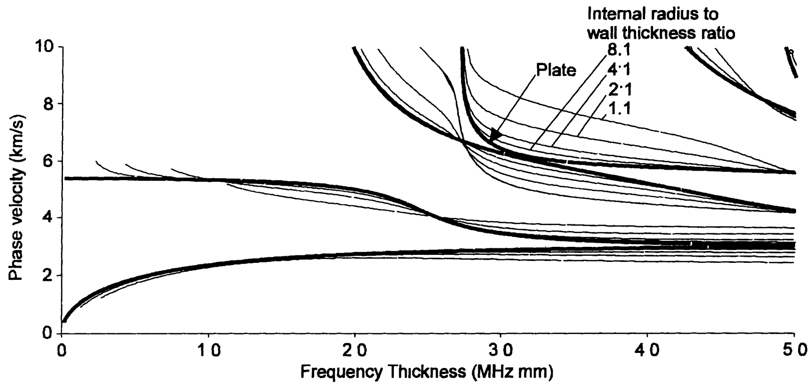

Fig. 1. Phase velocity dispersion curves for ductile iron plate in vacuum, showing the effects of curvature.

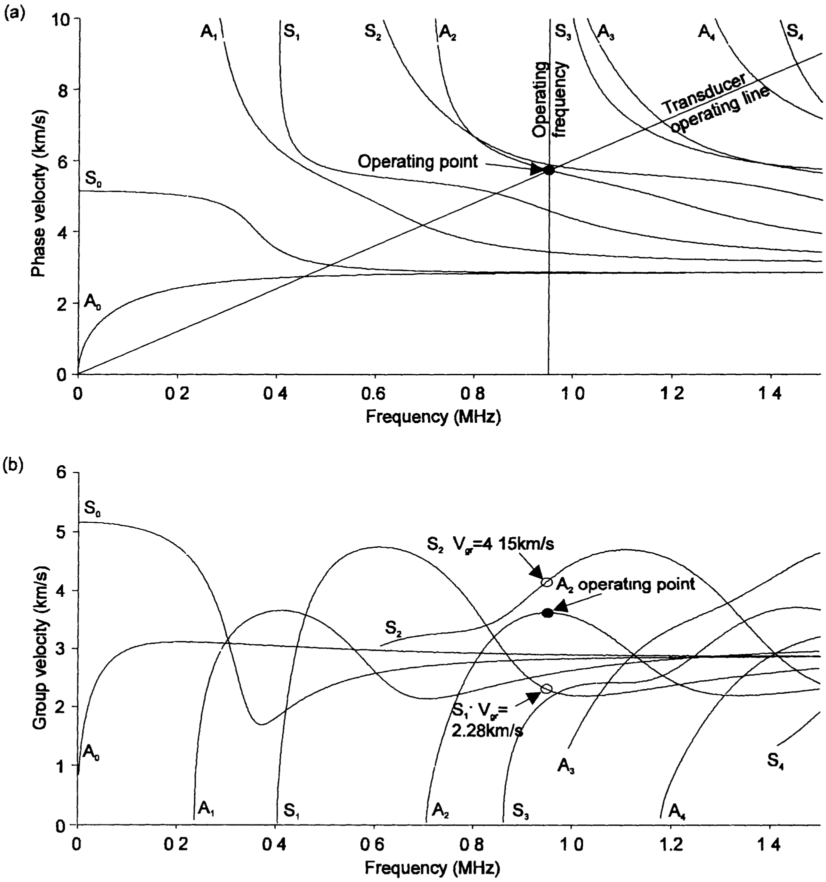

Fig. 2. (a) Phase velocity and (b) group velocity dispersion curves for flat 6.5mm ductile iron plate, showing target operating points and group velocities of adjacent modes.

The mode shape of a Lamb wave describes the amplitudes and directions of particle displacements through the thickness of the plate. To be used as an operating point, the mode shape at that point on a particular mode must exhibit a substantial proportion of out of plane motion at the plate surface compared to the amount of in plane motion. This is because the PVDF transducers are primarily only sensitive to out of plane motion. Another factor which must be considered when selecting an operating point, is whether other modes have similar phase velocities at around that frequency, as these may well be unintentionally excited and detected.

An initial study of the mode shapes at the non-dispersive points (i.e. at points of maximum group velocity) on modes S_1, A_2, S_2, A_3, S_3, A_4, S_4, A_5 and S_5 was made. In the higher frequency-thickness regime where many modes exist in close proximity it was thought preferable to use a symmetric ('S') rather than an anti-symmetric ('A') mode as the higher group velocities of the symmetric modes (see Fig. 2(b)) would enable them to be resolved from slower modes in time. However, on examination of the mode shapes of the symmetric modes using *Disperse*, it was found that none of the first three could be used, these modes only starting to have a significant fraction of out of plane motion with modes S_4 and S_5. Transducer pairs were made for operating points on both of these modes.

The first non-dispersive point on an anti-symmetric mode above 0.75MHz is at 0.95MHz on the A_2 mode, as indicated on Fig. 2. This point is in close proximity to the faster S_2 mode. However, A_2 has significantly more out of plane motion than S_2 in this region, so it was hoped that even if S_2 was excited it would be to a far lesser degree than A_2 and hence not a major problem. It is the results from transducers designed to transmit and receive the A_2 mode at 0.95MHz which will be covered from here onwards.

Design Of Transducers

Once the operating point was selected, the wavelength was calculated by dividing the phase velocity by the frequency at that point, giving in this case, a wavelength of 6.0mm. The dimensions of the transducer were decided next. The greater the number of fingers, the greater will be the wavelength resolution and the mode selectivity, but this must be weighed against the increased length of the transducer and loss of spatial resolution due to the increased spatial length of the signal. A compromise of 16 fingers (8 wavelengths) was used in this case, giving the transducer a length of 45mm. The width of the fingers increases towards the centre of the transducer to simulate the effect of a Hanning window around the spatial excitement. This improves wavelength selectivity by reducing the sidebands around desired wavelengths [2]. The width of the transducer was chosen to make it approximately square.

The electrical excitation signal (a 20 cycle tone burst at 0.95MHz) is shown on the left of Fig. 3(a) and its temporal Fourier transform to frequency space on the right. As a first approximation the spatial excitation was modelled by assuming that it comprised a discrete normal force at each of the finger positions of the transducer, the magnitude of which is proportional to the width of that finger, as shown on the left of Fig. 3(b). The spatial Fourier transform to wavelength space of this model is shown on the right of Fig. 3(b). The combined effect of both the wavelength and frequency resolution is then mapped onto the phase velocity dispersion curves in Fig. 4 as shown by the shading around the target operating point. It can thus be seen that rather than a single operating point, an operating zone exists which spreads to cover not only A_2 but also S_2 and to a lesser degree S_1, although as previously mentioned, the amount of excitation is dependant on the mode shapes of the various modes.

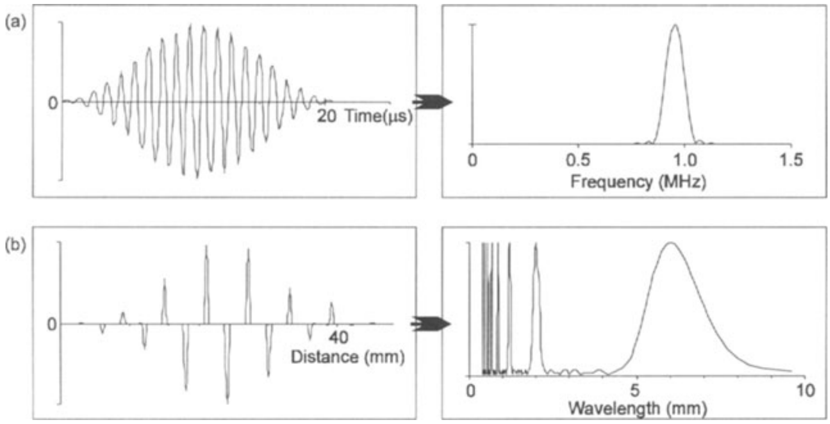

Fig. 3. (a) Graph of temporal variation of excitation signal (20 cycle toneburst at 0.95MHz) and its frequency content. (b) Graph of spatial variation of excitation (16 finger transducer, 6mm wavelength) and its resulting wavelength content. All scales are linear.

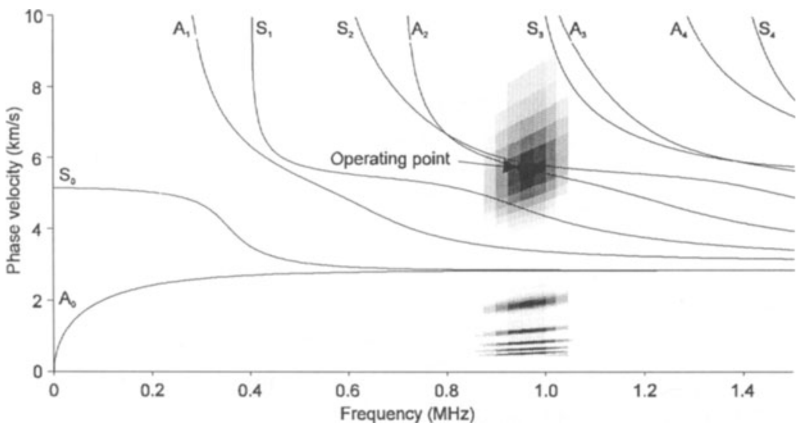

Fig. 4. The effects from Fig. 3 mapped onto phase velocity dispersion curves to give actual excitation zone of 16 finger transducer when driven with 20 cycle toneburst at 0.95MHz.

EXPERIMENTAL

Set Up

The experimental set up is shown in Fig. 5. The two transducers were identical so either could be used to transmit or receive.

The driving signal, a 20 cycle Hanning windowed toneburst at 0.95MHz, was generated by a PC controlled arbitrary function generator (a *LeCroy 9101*), the output of which was fed through a power amplifier (giving a peak to peak output voltage of around 100V) to the transmitting transducer. This signal is shown in Fig. 6(a).

The output from the receiving transducer was amplified by either 40 or 60dB in a pre-amplifier. It was then fed to a digital storage oscilloscope (a *LeCroy 9310A*) which was used to remove noise by time averaging a hundred successive signals. From the oscilloscope the data was downloaded to a PC for further processing.

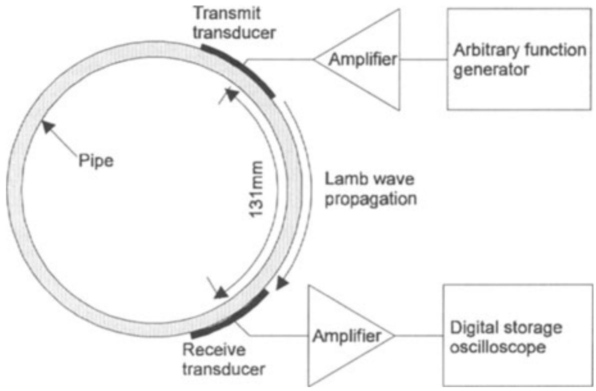

Fig. 5. Schematic diagram of experimental set up.

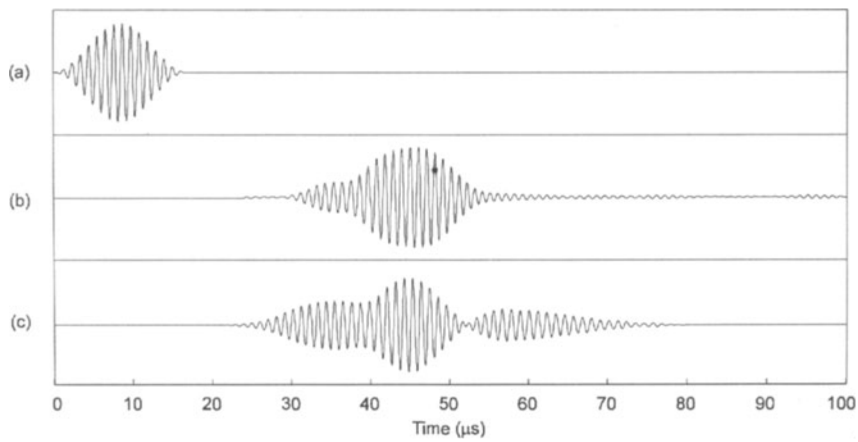

Fig. 6. (a) Excitation signal used in both experiment and FE model. Received time traces shown below are from (b) experiment and (c) FE model.

Results

The received time trace is shown in Fig. 6(b). More than one mode has been received, as can be seen by the signals on either side of the main peak. The time of flight from the centre of the driving toneburst to the centre of the main received peak (37μsecs) and the distance between the transducers (131mm) may be used to provide an estimation of the group velocity of this mode. This evaluates to 3.5km/s which compares well with that predicted for the A_2 mode at this frequency of 3.6km/s. The leading signal is an indication of a faster dispersive mode, which from the dispersion curves would appear to be S_2

FINITE ELEMENT MODEL

Set Up

The FE package *Finel* [7] was used to model the propagation of acoustic waves from the transmitting transducer through the structure to the receiving transducer. It uses an explicit time marching scheme. As the analytical dispersion curves show (Fig. 1), the effect of the curvature of the pipe is negligible. Hence, to reduce computation times, the pipe was modelled as a two dimensional plate structure under plane strain conditions, with excitation and monitoring regions approximately the same distance apart as the experimental transducers. The plate in the FE model was 6.5mm thick and 400.5mm long, this length being sufficiently great to ensure that acoustic waves reflected from the ends did not interfere with directly transmitted waves over the time period considered. The element size was 0.75mm in the direction along the plate and 0.65mm in the through thickness direction, giving a mesh size of 534 along the plate by 10 through its thickness. The 8-noded rectangular elements have quadratic shape functions.

The transmitting transducer was simulated by applying time dependant normal forces to a series of 16 nodes, one for each finger position. These forces were all 20 cycle Hanning windowed tonebursts at 0.95MHz (again as shown in Fig. 6(a)) but with alternating signs to simulate the 2 phase driving effect and with amplitudes proportional to the finger widths.

Monitoring was done in one of two ways. Firstly the receiving interdigital transducer could be simulated directly, by monitoring the displacements at nodes corresponding to its finger positions. These displacements were then summed with appropriate weighting functions to simulate the finger widths and signs to simulate the two sets of electrodes of the receiving transducer. The result was an FE prediction of an experimentally received time trace.

Alternatively and more usefully, the FE model could be used to examine which modes had been excited in the structure. To do this, displacements at 128 nodes around the approximate area of the receiver were monitored. The results from these points were then subjected to a two dimensional Fourier transform (2DFFT) [8] which converted them from times and distances into frequency-wavenumber space. This procedure enabled modes to be identified which could not be separated in either the time or frequency domains.

Results

The FE prediction of the time trace from an interdigital receiver is shown in Fig. 6(c). In common with the experimentally obtained equivalent in Fig. 6(b), at least two extra modes appear to be present in addition to the desired A_2 mode. The amplitudes of both of these modes are higher compared to that of A_2 than in the experimental time trace. The reasons for this discrepancy are still being investigated.

A three-dimensional plot of the 2DFFT results is shown in Fig. 7. Again the excitation is a 20 cycle toneburst at 0.95MHz. The three peaks show that, as suggested by the time traces, three modes have been excited. Mapping the wavenumber axes to phase velocity enables the 2DFFT results to be compared directly with the analytically obtained dispersion curves as shown in Fig. 8, and hence the three peaks identified as A_2, S_2 and S_1.

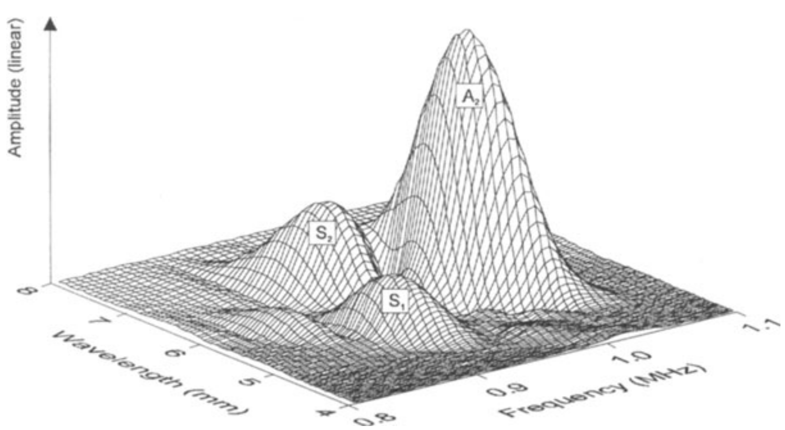

Fig. 7. 2DFFT performed on FE results, showing that the additional modes S_1 and S_2 are both excited, but to lesser degrees than the intended A_2 mode.

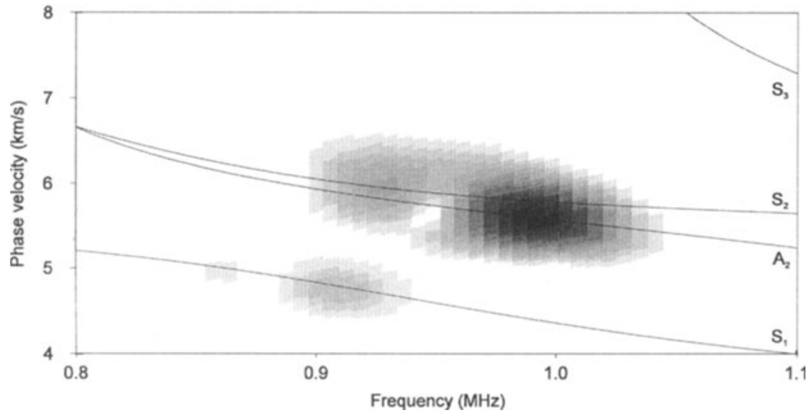

Fig. 8. Results of 2DFFT shown in Fig. 7. mapped as a grayscale onto phase velocity dispersion curves.

CONCLUSIONS

Details of an example application of the use of interdigital transducers on a thick curved structure have been presented. Good excitation and detection by the transducers has been achieved, and there is considerable potential for using this type of transducers to instrument flat and curved structures. The use of FE modelling techniques has also been demonstrated and good agreement between analytical, FE and experimental results has been achieved. This example is not an ideal application of the transducers due to the thickness of the structure, but even so, it has still proved to be quite successful.

Future work will investigate whether similar transducers could be used to generate a greater degree of in plane motion in a structure, and to examine other methods of boosting their low frequency response.

ACKNOWLEDGEMENT

This work was completed under the Postgraduate Training Partnership (PTP) scheme between Imperial College and the Water Research Council (WRc), with support from the United Kingdom Engineering and Physical Sciences Research Council (EPSRC).

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